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representing and studying the urban void**

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CONVEX AND SOLID VOID DOMAINS OF APPLICATION

REPRESENTING AND STUDING THE URBAN VOID

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Abstract: Convex Voids are derived from convex 3D informed representations of public space. Contrary to space syntax traditional convex spaces which take the fattest spaces (spaces with the fattest inscribed circle) for their definition, convex 3D informed spaces resort to a 'fattest+squareness' algorithm to generate their representations based on an aggregation of triangles, which is able to recognize two streets crossing as individual spaces defined by the street corners. They are informed because they derive from geographic information and therefore can have associated information, plus additional information that might be derived from analytical procedures. And they are 3D informed because they contain information on elevation, slope, boundary elevations and neighbour spaces (plus inherited GIS information). This information is used to generate an extrusion of the convex space into a three dimensional representation called Convex Void. Solid Voids are aggregations of convex voids. Consequently, solid voids tend to cross each other at street crossings generating a network representation where solid voids can be characterized by the number of convex voids defining them expressing continuity, the number of connections with other solid voids expressing connectivity and the topological distance from other solid voids expressing network depth. A systematic study of spatial types and their boundary conditions based on solid void models may provide new insights regarding an understanding of public space behaviour and its design conditions for the development of citizen friendly urban spaces..

Keywords: CIM (City Information Modelling); Spatial analysis; Convex and solid void analysis.

1. Introduction

Convex and Solid Void (CSV) representations constitute an algorithmic approach to evaluating open space. This formalism finds a way to represent the void between buildings taking their facades as boundaries to represent spaces as volumes. As a model of reality it represents as solid only the void and as such stands as a representation of open space amenable for several levels of analysis. Additionally, these representations embed georeferenced data taken from GIS databases and most importantly contain data on the built environment shaping the void representations including figures on the façades shaping the void. CSV models are algorithmically generated and therefore constitute uniform informed representations of public open spaces amenable for spatial analysis.

Convex Voids are derived from what can be termed 3D informed convex representations of public space. Contrary to traditional space syntax convex spaces that take the fattest spaces (spaces with the fattest inscribed circle (Hillier and Hanson 1989) (Turner, Penn, and Hillier 2005)) for their algorithmic definition, convex 3D informed spaces resort to a '*fattest+squareness*' algorithm to generate their representations based on an aggregation of triangles, which is able to recognize two streets crossing as individual spaces defined by the street corners. They are informed because they derive from geographic information and therefore can have associated data, in addition to information that can be generated through analytical procedures. They are 3D informed because they contain information on elevation, slope, boundary elevations and neighbouring spaces (in addition to inherited GIS information). Together this information is used to generate an extrusion of the convex space into a three dimensional representation called the *Convex Void*.

Solid Voids are aggregations of convex voids. Aggregations occur whenever three conditions are satisfied: (1) continuity between spaces given by a low angular horizontal deviation; (2) continuity between spaces given by low vertical deviation; and (3) connectivity between spaces given by similar scale of boundary share. Condition (1) keeps natural flow continuity even in the case of winding streets (comparable to visual continuity). Condition (2) distinguishes street sections broken by topography (e.g.: in San Francisco streets, although linearly continuous, break at hill tops and deep valleys, distinguishing two visually independent sides of the same street). Condition (3) breaks continuity between spaces with a different scale. The latter condition allows the distinction between streets and squares.

Consequently, solid void representations tend to cross each other at street crossings generating a network representation where solid voids can be characterized by the number of convex voids defining them expressing continuity, the number of connections with other solid voids expressing connectivity and the topological distance from other solid voids expressing network depth.

Such networks may be the representational basis for topological analysis (similar to space syntax). However, the nature of these representations is particularly fit for analysing public space at the neighbourhood level,

complementing the information directly derived from the representations with additional GIS information and more specifically with information regarding the solid voids' connecting elements, i.e., buildings and other private spaces and limits.

A systematic study of spatial types and their boundary conditions based on solid void models may provide new insights regarding an understanding of public space behaviour and its design conditions for the development of sustainable and citizen friendly urban spaces.

2. Motivation

CSV models derive from a criticism opened towards space syntax by Carlo Ratti (2004) where a set of flaws in the theory were at that point formally put forward. Among other points, the fact that space syntax works on flat representations ignoring topography and the height of buildings becomes an important limitation while working at close scales like neighbourhood, fabric or even just street scale. The counter-argument (Hillier and Penn 2004) stating that the street configuration already contains the information arising from the topography does not solve the insufficiencies derived from the lack of detail. The adaptation of the traditional space syntax model closer to three-dimensional space to include multiple connected levels of pedestrian flow for instance (yet still disregarding topography), can produce dramatic changes in the network representation and consequent measures, as has been recently demonstrated by Zhang and Chiaradia's (2020) study into complex volumetric urban environments. Another critical point regarding the space syntax convex space representation states that the *fattest* space algorithm is not capable to capture in the representation the singularity in spatial experience of two streets crossing each other in a regular grid, nor there is any formal representation in space syntax to address the changes in spatial containment created by alternating building heights while moving through a street. However, the '*fattest + squareness*' algorithm applied in the generation of CSV models seems to capture in a distinctive manner all junctions in the street network and therefore provide a much more consistent representation for studies on perception of spaciousness and containment while moving in space.

At its origin, the creation of CSV models to represent and study public space came from the research goal of studying feelings of arousal provided by sudden changes in spatial containment or openness towards distant views. The need to generate such representations algorithmically came from three essential aspects: (1) obtaining uniform consistent representations; (2) being able to deal with large amounts of data; and (3) link such models with available georeferenced data. There was also at this initial stage the idea that we could develop an automated classification approach for classifying a typology of urban spaces in the same way we had done for the automated classification of building types either by following a shape based approach (Chaszar and Beirão 2013).

3. Analysis fields and themes

CSV data models therefore define new opportunities for analysis and seem to be particularly appropriate for scales where 3D detail becomes important, namely, neighbourhood, fabric and street scale.

Following the above mentioned characteristics, CSV models open up two avenues of research: (A) software improvement and validation (for developers); and (B) the exploration of their application potential on urban studies addressing the following analysis fields and themes (for urban study end users):

1. Street plinth impacts on street safety and street dynamics;
2. Impacts of façade design on public space dynamics;
3. Study of impacts of objects in space (both static and moving objects);
4. Studies on visual perception in space, such as feelings of arousal upon spatial openings and towards distant subjects or infinite views;
5. Walkthrough stimulus and design strategies for walkthrough stimulus; walkability studies;
6. Public space sustainability by studying biomaterial coverage and permeable surfaces together with solar exposure (including street cross section design);
7. Morphological studies – spatial void classification. Finding correlations between patterns of behaviour and void patterns.

Research area A is essential for area B because it provides the supporting software. The role of the software is twofold: 1. Generate the representations (and data); 2. Run analytical procedures making use of the generated representations and available data. However, the existing software, despite its many improvements and use in academic environments, still need further debugging, performance and interface improvement as well as validation, the latter being the most urgent step to take in order to consolidate theory and relations to other existing theory on spatial analysis. The 'Future Work' section will add some information about research area A.

As to research area B, in the next subsections we develop further these fields and themes while planning future work.

3.1. Street plinth impacts on street safety and street dynamics

It became quite clear since Jan Gehl's seminal work on public space (Gehl 1971) that the design of the street plinth, or in other words, the design of buildings' ground floor plays an essential role in determining how passers-by relate to the building and people in the building relate to public space. Jane Jacobs (Jacobs 1961) had also pointed out how important it was for public space safety to have the building users, either workers or householders, with the ability to look down to the street and observe passers-by. These comments imply that some features must be reckoned and implemented in the design of the buildings' ground floor. Alex Lehnerer (Lehnerer 2009) points out some rules in this regard, namely (1)

that buildings should have windows facing the streets; (2) that facades at street level should not be opaque for more than 20 meters; (3) that entrances should face as much as possible directly to the public space; (4) transparency at ground level is positive (Lehnerer points out a minimum percentage); (5) that façade diversity improves the street ambience. Beirão and Koltsova (2015) show that residential areas tend to reserve or segregate a bit the entrances from the street while commercial areas open directly to the street space. The size of the sidewalk also matters. If the sidewalk is large enough commercial activities at ground level may ‘drool’ towards the sidewalk (like fruit or vegetable stands, or esplanades).

Studies on the impacts of plinth design can make use of CSV models and associated information to: (A) study existing conditions; (B) find affordances for commercial activity; (C) find patterns of building plinth design and establish correlations to patterns of public space behaviour; (D) decision support analysis for street cross-section design (or public space design); (E) study gated community impacts on public space.

Each of these topics shall have its proper research methods of applying CSV models to their specific research questions. Topics A and E typically work on existing conditions and try to understand their impacts on street safety and street dynamics in general. They try to understand their object of study, the public space, as it is – without changing the object or its conditions. Topics B, C and D depart from the analysis of the existing conditions to extract intelligence that might support decision making on possible transformations on the object of study. B and C look for correlations between morphological patterns and behaviour and D applies that knowledge to design. D may be developed by integrating tools such as CIM-Street on CSV tools (de Klerk and Beirao 2017) (Beirão and de Klerk 2017). C may also resort to Beirão and Koltsova’s tools for territorial depth and ground floor analysis.

3.2. Impacts of façade design on public space dynamics

The essence of this theme is the same of the previous one but applies most principles to the entire façade and not just to the plinth. The façade design as a whole and its impacts of public space dynamics become the main object of concern.

It is in this field that we address questions like how much does Architecture impact the quality of the public space? And, can we pinpoint specific conditions that are required to obtain good or positive public space dynamics?

Additionally, we can also study, details on the façade transparency and design, as well as its orientation regarding the public space, distance from openings to the public space (is there visual recognition? is it possible to communicate from window to the street?), façade size (as part of the topic of diversity) and so on. As in the previous research field, these aspects can be studied resorting to CSV models by capturing related data associated to each convex or solid void.

The assumption establishing the research hypothesis states that void patterns and façade design may have correlations to behavioural patterns – with void patterns understood as morphological patterns and behavioural patterns as spatial dynamics systems.

This research could be combined with Morpho, a street analysis methodology that combines morphology and configuration features into a 'morphological + some *behavioural*' analysis of streets (Oliveira 2013) (Oliveira and Medeiros 2016). Suggestions given by Oliveira in these publications are rather straightforward to implement to the present state of software development.

3.3. Study of impacts of objects in space (both static and moving objects);

Public open spaces are rarely empty. They contain many different types of objects from fixed and rather permanent ones (e.g.: trees, benches, kiosks, etc) to temporary or even movable and/or moving objects (e.g.: food trailer, temporary sales stand, etc). It is empirically evident that the presence of these objects change the perception and feeling of the space and that they affect its use. The impacts of the presence of these objects in public space is rarely studied with objective methods and tools, possibly because such studies require objective ways of representing the space under study and not, as it usually is, the representation of the things within the space or containing the space. CSV models bring a uniform representation of the space into the analytical methods focusing on spaces as 'things' themselves.

3.4. Studies on visual perception in space – feeling of arousal upon spatial openings and towards distant subjects or infinite views

This theme increases the protagonism of space as object of research and focuses on the relations between an observer and the impacts of changes in feeling of opening and/or containment in spatial experience while moving through space. Spatial transitions and their impacts on navigation or pedestrian experience may be studied more objectively once we depart from an objective uniform representation of public spaces and their respective relationships not only between accessible/connected voids but also from void to inaccessible voids or restricted views towards distant horizons (vision across lakes and rivers, waterfronts in general). Distention and compression of space can therefore be studied together with behaviour and eventually find that certain types of compressed or open space and transitions between one and the other might show consistencies in pedestrian experience. Particular qualities of urban spaces deemed to cause feelings of arousal upon unexpected openness to wide distant views or towards singular objects¹, usually studied by means of phenomenological subjective observation, may acquire objectiveness once the spatial representations become algorithmically standardized and subjected to objective analytical methods calculating properties and indicators that correlate view sheds and vision in motion within spatial voids to patterns of behaviour

¹ The effects of entering spaces like Piazza del Campo in Sienna, Piazza Navona in Rome or Praça do Comércio in Lisbon may be studied with less subjectivity.

(e.g., Visual Graph Analysis – VGA (Turner et al. 2001) (Turner 2001) (Turner 2003) (J. Lopes, Paio, and Beirão 2019)).

Assuming that these phenomena are understood by most people with a simple explanation, and that we can in most cases understand why some spaces produce specific feelings, we cannot however pinpoint the exact details and shifts in spatial morphology that induce such feelings. However, it would not surprise us to find that particular characteristics of space are related to particular types of feelings. Still, turning such empirical notion into accurate design instructions is a subject that requires objective research athwart a wide number of cases to find patterns and consistencies among phenomena.

This research may be enhanced by collaboration with neuro-sensor first hand experiments to collect primary data on visual response to spatial changes (either distension, compression or sudden appearance of objects in the visual field).

Methodologically speaking, this type of research follows the sequence of procedures given below:

- a) Data collection. This involves (1) identifying and characterizing case studies morphologically, and (2) collecting phenomenological data on behaviour in such spaces (sensorial data and other types of primary data, view sheds, visual analysis data, VGA).
- b) Identification of morphological patterns (space typology classified in terms of CSV representations).
- c) Identification of phenomenological patterns (types of sensorial responses to visual stimuli, types of visual stimuli, types of visual fields).
- d) Search for correlations between spatial types and types of visual fields.
- e) Search for correlations between types of visual fields and types of visual stimuli.
- f) Search for correlations between types of visual fields and types of sensorial responses to visual stimuli.
- g) Analysis of results, discussion and theory building.

Similar methods may be applied to themes 1 to 3.

3.5. Walkthrough stimulus and design strategies for walkthrough stimulus; walkability studies

The previous theme might be seen as a particular case of the present one. Walkthrough stimulus can be seen as a very generic approach to studies on visual stimulus for navigation and for pedestrian navigation in particular. Such types of studies already have some background by using VGA for studying navigation within museum spaces, but in this case the idea is to bring them to the public space and find patterns of stimulus to movement by identifying what features of particular types of spaces induce what types of movement.

By opposition, we may consider studies on what types of spaces and what types of visual stimulus in spaces induces a pedestrian to stay, perhaps an even more important information when designing public open spaces.

This research space can easily be extended to walkability studies or studies aimed at finding correlations between behavioural patterns and spatial morphotypes. Ensari Sucuoğlu (2020) used CSV models and an additional 'Street Void' representation combining the same algorithms with segment maps to map '*social behaviour*' based on social media data in order to study walkability in four different neighbourhoods (two from Lisbon and two from Istanbul). This research was recently completed using CSV models as the base representation of space to run the analyses.

3.6. Public space sustainability by studying biomaterial coverage and permeable surfaces together with solar exposure (including street cross section design)

This theme introduces a different type of interest and research objectives as it introduces the topic of the production of sustainable cities especially from an ecological viewpoint. It builds its methods on the fact that CSV models aggregate data on spatial morphology and any additional data on surfaces bounding or defining the space, together with data extracted from GIS databases or even secondary data on solar exposure derived from the generated 3D models. By collecting data on solar exposure across seasons and generating variations on biomaterial coverage of the public space (green permeable surfaces) and/or tree coverage we can study the impacts of such variations on street environmental performance and eventually instruct recommendations for street cross section design.

An ultimate goal would be to optimize street cross section design in terms of sustainable performance (environmental, social, economic) – an objective that would require mixing some of the tools and methods mentioned in the previous themes.

3.7. Morphological studies – spatial void classification. Finding correlations between patterns of behaviour and void patterns

At most, all previous themes end up (methodologically speaking) in this one. The main principle is that through CSV representations we can develop a typology of public spaces by finding (statistical) patterns among its morphological features. Each type (or pattern) provides not only a possible morphological classification but also gives us the specific features and values for each pattern's archetype and the domain variation of the type. Once a typology of public space is accepted, additional data addressing performance, environment and user behaviour can be brought up through similar processes of pattern finding, in this case by identifying patterns of behaviour, social patterns, environmental patterns and alike. Correlations between patterns of space (void) and patterns of behaviour may then be searched for.

There is no reason to believe that there is a single (best) statistical method to obtain the best (most informative) results, nor is there a reason to believe that there is a specific sequence of procedures that will provide the best (most informative) results. The choice among methods and sequences of methods shall essentially depend on the specificity of the research question posed for investigation. Conversely, one may start from the assumption that we do not know anything about public space and let the intelligence emerge from the way we treat the data. In other words, assuming that the statistical methods will highlight how performative features cluster within patterns and that those clusters or arrangements of features correspond to clear behavioural data possibly confirmed by primary evidence, one may start elaborating a theory where spatial features correlate to specific types of behaviour and therefore build a new theory of data based (but also performance based) design.

4. Brief Literature Review

CSV models are a recent concept developing public open space 3D representations with georeferenced data amenable for spatial analysis. The concept emerged from the need to represent the void in order to study visual perception in public space. Hence, the first study where this concept was used² addressed theme 4 (Cavic 2018). At the initial stages of this research several difficulties hampered a uniform consistency among representations, even during the first algorithmic implementations. At a certain point a strong effort had to be put on developing a software implementation for the generation of uniform CSV representations (by uniform we mean consistent representations generated by a single algorithm). The first implementation was developed as a compound set of algorithms based on QGIS, Rhinoceros and Grasshopper by resorting essentially to python 2 algorithms. Details are available at (Sileryte, Cavic, and Beirao 2017). This platform was applied between 2018 and 2021 on an elective course on spatial analysis methods given at the Lisbon School of Architecture, University of Lisbon.

The generation of CSV representations (and requisite software) follow a specific workflow given at (<http://solidvoids.fa.ulisboa.pt/tutorial/>³), simplified here as: **① 3D Geometry of Built Environment** (3 layers: Buildings / Topography mesh / Walls) → **② QGIS, 5 Algorithms to produce public space triangulation** (1. Urban limits; 2. Topology; 3. Topography; 4. Cognitive points; 5. Triangulation) → **③ Triangulation is imported to Grasshopper** → **④ 3D Informed Convex Space Generation** → **⑤ Convex Void Generation** → **⑥ Flows generation** → **⑦ Solid Void Generation** → **⑧ Analytical Functions** (e.g.: Sky View Factor; Containment; Openness (Beirão, Chaszar, and Cavic 2014) →

² Actually emerged from the study.

³ This page has been under constant update as the software develops and was intended always as a support for academic-user-developer type of users. This page contains in principle always the last stable version.

⑨ **Data export and storage** (as 3D models for reuse, data tables and shapefiles for additional analysis).

① This is essentially 3D modelling (on Rhinoceros) preferably modelled from GIS based geometry, so that georeferenced data may be kept in association to the geometry. The layer 'Walls' refers both to walls limiting properties or containing-walls containing different topographic levels in public space. A fourth layer, Horizontal-Limits, referring to water limits (riversides, lakes, pools, waterfronts in general) was theoretically defined (and applied in the first implementation) but waiting for debugging in the last implementation and therefore not available at the moment.

② These algorithms are applied in QGIS after running an algorithm that generates the layers' shapefiles. QGIS project is initiated by creating these layers or added to pre-existent QGIS project.

③ and ④ The generation of convex spaces from the public space triangulation resorts to an algorithm that uses an exponential search space. Therefore, the triangulated space has to be broken into several layers that are treated separately. The breaking of the triangulation layer into several layers is at the moment a handmade selection and therefore the most time consuming task of the whole procedure, but actually saves time within the overall procedure because algorithm ④ runs a lot faster. As a matter of fact, algorithm ④ may easily slide into non tractable computation time. Hence, the breaking procedure is essential. However, an algorithm is under study for automating the breaking procedure.

Algorithms ④ ⑤ ⑥ ⑦ and ⑧ keep tracking data over the generated shapes and store that data in relation to the generated shapes. Algorithms ④ ⑤ ⑥ and ⑦ generate specific layers - **Convex Spaces**; **Convex Voids**; **Flows**; and **Solid Voids**. Once algorithm ⑨ exports the shapefiles for each layer all the additional generated data including the tracking data is associated to the respective layers and may be assessed in both Grasshopper and QGIS environment. Algorithm ⑨ also generates excel tables of that data providing a data access link with any other platform or even back to Grasshopper simplifying data retrieval.

Presently, the software has been upgraded to python 3, solving many interoperation incompatibility problems that were emerging from the former python 2 version. It has also been improved in terms of user interface allowing one to press a set of instructions along a sequential set of pop-out windows. As such, the present format of the software already provides space for two types of users: the developer and the spatial analyst.

Additional details may be found at: <http://solidvoids.fa.ulisboa.pt/tutorial/>

5. Future Work

On (A) software improvement and validation (for developers)

At the present stage the existing software still requires a lot of work. This not simply software development because most of the software development complexity derives from the complexity of urban spaces and therefore this research requires guidance and coordination from urban spatial analysis specialists. The software has been used successfully to represent regular grids, traditional medieval grids and waterfronts. Still, there hasn't been enough work on modern grids and such types of urban space definitely require special attention as they might bring ambiguities in terms of private-public space limits as well as height interpretation of buildings deep inside a private space. Such possible difficulties require a systematic approach to other grid types. The present challenge (under development) is the systematic representation of CSV models for the entire city of Lisbon, starting from the city centre towards the periphery, which shall progressively cover all types of urban spaces both morphologically speaking and topographically speaking.

As a simultaneous important software development task, there is a set of specific details within the software that leaves open several options during CSV generation. These options appear whenever there is an algorithm to be applied. There are 3 types of options applied along the many algorithms: (1) - tolerances; (2) - options on triangle aggregation (levels of superiority); (3) - alternative ways of calculating height for convex void extrusion.

All options were left open in the software for two essential reasons: first, because they might all be found useful depending on the research or representation purpose; and second, because they all still require a consistency validation. Tolerances apply almost in every algorithm (including all 5 QGIS algorithms). They provide different levels of detail and accuracy, and might be just used for reducing computation time. The main idea is to freeze these options at some point once we find enough evidence that a certain set of tolerances provide the best results, meaning the most consistent representations. To establish such decision, we simply need to accumulate evidence and check the consistency for all possible variations. The main objective is to freeze tolerances for the regular urban analysis user. Again, two points justify this objective. (A) analysis comparability requires that all models under analysis result from the same algorithmic definitions; otherwise results cannot be compared. (B) once all users apply the same tolerances, their analytical results can also be compared between different research teams as we do with space syntax analysis.

Levels of superiority refer to the algorithmic criteria used in triangle aggregation when generating the convex spaces (see Sileryte, Cavic, and Beirao 2017). The software keeps several options open that produce different results. '*Fatness*' produces a result similar to traditional space syntax convex spaces. '*Fatness + Squareness*' produces the results that best represented the spatial singularity of the street junctions, a topic that was at the root of the conceptual

development of CSV representations, and is therefore the model we want to further pursue. However, in this case we thought that it could be useful to keep these options open as other researchers might find research problems where other levels of superiority may prove to be more resourceful. Furthermore, the use of '*Fatness*' might be useful to compare results obtained from Depthmap (Turner 2004) with those obtained from CSV's '*Fatness*'. CSV levels of superiority additionally provide '*Fatness + Compactness*', '*Squareness*' and '*Compactness*' initially used for exploring several types of representations. The obtained variations showed that the results obtained using '*Fatness + Squareness*' were the ones we were looking for. Still, it seemed to us useful to keep these options for researchers involved in advanced exploration of convex space representations and other possible analytical uses. Finally, the triangle aggregation procedure follows a set of triangle selections from the whole mesh (as explained in the steps ③ and ④) that could be automated to reduce possible ambiguities⁴. The automation of this procedure is therefore still a software improvement objective already on the future work agenda.

Convex void extrusion also presents a set of algorithmic options: (A) average height; (B) maximum height; (C) minimum height; and (D) weighted average height. The three first algorithms were the ones we used initially while still exploring which representations could more consistently render the feeling of containment generated by the facades in a street. Algorithm C was soon discarded because it would take zeros in most cases and would produce meaningless representations. The weighted average version developed from results regarded by us as inconsistencies in terms of the representation of '*spatial containment*'. This issue is further detailed on (Beirão, Chaszar, and Čavić 2015). This inconsistency was particularly clear on crossroads on narrow regular grids where the space corresponding to the crossroad faces the void of 4 streets and therefore is not shaped by facades – the average height of facades is therefore zero. However, the edges of the corner buildings produce some kind of virtual containment even though such feeling might be reduced by the views towards the four street segments meeting at the crossroad. This feeling will be stronger if the streets are narrower and lighter when streets are wider. The weighted average algorithm picks the average height of the neighbouring spaces and adds a weight factor based on their difference and a quadratic function of the space area that weights heavier on smaller spaces than larger spaces. As an alternative option and perhaps a more meaningful representation is to take the mode value of facades' height. This is planned to be implemented in replacement of algorithm C.

⁴ In order to reduce ambiguity there is a rigorous set of instructions for the manual selection of triangles which, when followed, reduces almost every ambiguity. Also, when working on well-known territory this procedure allows for human checking of inconsistencies on the original data providing opportunity for correction. However, comparability between models becomes dubious without an automated procedure.

Currently there is a set of analytical tools already planned to be implemented in extension to those that have already been developed. The idea is to include as much as possible as set of typical analytical functions with an easy user interface including mappings of such calculations and data export tools. Many tools already exist and require only connection, interface design and data processing (visualization and export). On the agenda, there is also the idea of implementing some of the analytical procedures developed by João Ventura Lopes (J. V. Lopes et al. 2017) (J. V. Lopes et al. 2015) (J. Lopes, Paio, and Beirão 2019). Additionally, and considering the research theme 6 on public space sustainability we will study methods and develop the necessary algorithms to add material properties to the horizontal surfaces of Convex Voids. This single topic may in itself be a rather complex research project.

Finally, we fully recognise that whilst our methodology is firmly entrenched within the predominantly academic field of structural morphology, its use in the multiple disciplines constituting urban science, from history, economics, and sociology to administration, architecture, and environmental engineering, has the potential on the one hand to augment their respective toolset, and on the other to provide valuable ancillary data on the city, potentially opening up new avenues of research in the respective fields. This requires the employment of our toolset by actors unaccustomed to complex and highly technical software used in three-dimensional analysis and geo-informatics from which it originally sprung. We have completed the first stage of this process by automating a number of functions and introducing a simplified user-interface both in the QGIS and Rhino 3D environments. Our long-term plan is to develop a version independent from both those software environments and easily accessible to any user through a standard web application. Whilst this is a complex and lengthy undertaking, the first stage (which removes the QGIS dependency) has been completed and we are currently investigating options for the second stage of removing the Rhino 3D dependency. Concurrently, there is a need to develop interfaces to connect the CSV model with multiple data input sources, to further automate the generation of the CSV model and augment the model itself, and output targets, to bridge gaps with other disciplines through standard analytical tools, develop automated reports, and feed calculations back into the original source database.

On (B) urban studies (for urban analysis users)

We believe that the current status of the CSV toolset has attained a level of stability and usability to warrant its application in urban studies from the city to the neighbourhood scale by researchers, analysts and public or private actors in several fields, from land-use and transportation, through health, environment and urban policy, to exploratory spatial analysis into the physical yet intangible continuous space that constitutes the circulatory system connecting individual spaces, their functions, occupations, and inhabitants, within the contemporary city. We have already outlined seven possible research themes in section 3 of this paper focusing on: (1) street plinths, (2) facade design, (3) spatial obstruction,

(4) visual perception, (5) walkability, (6) permeability, and (7) void morphology. For the urban analyst, at the moment such studies are necessarily exploratory in nature and therefore best conceptualized within a synergetic approach to pattern recognition (Haken & Portugali, 1995). This is best seen in theme (7) through the construction of a systematic approach to representing and interpreting void morphology, and currently constitutes our next step through the generation of a CSV model of the city of Lisbon. Whilst we will be concentrating on pattern recognition and classification, the data generated by our future CSV model of Lisbon will equally serve as the first stone in the future assembly of a series of much-needed validation tasks, through comparisons to field observations as well as alternative methods of spatial analysis.

Such validation tasks include determining correlations between CSV measures and traditional space syntax metrics (such as Depth, Integration, Choice and Control) and validating both sets to ground-truth observations such as pedestrian and vehicular counts, traffic flow surveys, as well as socio-economic indicators, with a particular focus on the correlation between these measures and the CSV model on the one hand, and the identification of breaks within the CSV void representation that may represent inequities within the management of urban resources and planning. We are currently exploring possible locations for studies which embrace themes 4, 5 and 7. Likewise, further work on themes 2, 4 and 6 would represent a welcome deviation from to socio-economic urban research to focus on environmental validation and calibration of particular CSV representations against solar exposure analysis refinement (currently limited to the implementation of a Sky View Factor) and calibration of existing Containment and Openness measures. Finally, there is a need to develop new CSV measures to take into account spatial obstructions and additional cognitive qualities, corresponding to themes 1 and 3, which at the moment merely exist as theoretical foundations and statements of intent but which can be easily implemented onto the current toolset, assuring their consistency and performing the necessary validation.

6. Closing Statements

The CSV model was initially developed to bridge a gap between network models and urban morphology, most evident in the boundary conditions of sudden changes in spatial containment and openness. It quickly evolved to offer solutions to long-standing criticisms of space syntax models initially summarised by Carlo Ratti, all of which are present within the close confines of the city of Lisbon where our model originated. The adaptation of the traditional space syntax model into three-dimensional space to include multiple connected levels of pedestrian flow can produce dramatic changes in the network representation and consequent measures, as has been recently demonstrated by Zhang and Chiaradia's (2020) study into complex volumetric urban environments. We now believe we have reached a stage in the construction of the methodology, its toolset, and the rapid expansion of available data to open up new avenues of research addressing the challenges presented to urban residents worldwide and provide a rigorous data-driven

model for effective science-based public policy. This will require the collaboration of multiple actors and agencies involved not only in city management and design, but principally, in the aggregation of geolocation data such as the real estate and retail sectors, the telecommunications and transportation sectors, and the public service, urban planning, and research sectors, providing us with the ability to augment the cognitive model with associated behavioural data, calibration, and validation, ultimately allowing for the generation of a silica counterpart of existing cities for fine-grained analysis and strategic simulations.

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